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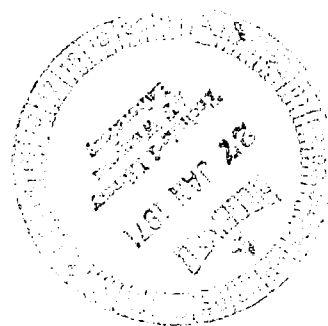
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**FORCES DUE TO AIR AND HELIUM JETS
IMPINGING NORMAL TO A FLAT PLATE
FOR NEAR-VACUUM AND
SEA-LEVEL AMBIENT PRESSURES**

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16. Abstract <p>An investigation was conducted in the 12.5-meter-diameter vacuum sphere at the Langley Research Center to determine the loads produced by air and helium jets impinging normal to a flat plate at ambient pressures of 5×10^{-4} torr, 225 torr, and 760 torr. The far-field loads were nearly constant for each nozzle tested and were about 40 percent greater than the gross thrust of the nozzles (without spillage off the plate) under near-vacuum conditions. Near-field and zero-height loads were dependent on nozzle-exit area and nozzle chamber pressure and therefore were very high for the hypersonic nozzles. The maximum touchdown load was 60 times greater than the thrust for the Mach number 12 helium nozzle in a near vacuum.</p>					
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NORMAL TO A FLAT PLATE FOR NEAR-VACUUM
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SUMMARY

An investigation was conducted in the 12.5-meter-diameter vacuum sphere at the Langley Research Center to determine the static loads or forces due to air and helium jets impinging normal to a flat plate at ambient pressures of 5×10^{-4} torr, 225 torr, and 760 torr ($1 \text{ torr} = 133.32 \text{ N/m}^2$). These pressures corresponded to altitudes of 95 km, 9 km, and sea level. The nozzles had nominal exit Mach numbers of 1, 3, 5, and 7 for air and 1, 3, 7, and 12 for helium. The vertical distance of each nozzle above the plate was varied from touchdown (zero height) to about 200 throat diameters.

The variations of the ratio of normal force to gross thrust with height were similar for corresponding air and helium jets. The far-field loading effects began at heights above the plate equal to about 0.2 exit diameter, were constant, and produced 40 percent more normal force than average gross thrust of the nozzles (without spillage off the plate) under near-vacuum conditions. The near-field forces varied markedly with distance and nozzle-exit area. The touchdown loads under near-vacuum ambient pressures varied from a value equal to the gross thrust for the Mach number 1 air or helium nozzle to a large value equal to 60 times the thrust for the Mach number 12 helium nozzle. Raising ambient pressure reduced the flat-plate loading and, under certain near-field conditions, produced lift.

INTRODUCTION

The need for more basic jet-impingement load data for the design and optimization of reaction control systems and structures for space and reentry vehicles has led to an experimental study in the 12.5-meter-diameter vacuum sphere at the Langley Research Center. Considerable experimental and analytical work has been done in the past to determine the effect of jet impingement on the pressures, temperatures, heat transfer, erosion, impact damage, flow field, structure, and cavitation of nearby or adjacent surfaces including lunar or Martian soils. Examples of recent papers on these subjects are given in references 1 to 12. Few or no data are presently available on the total loads or

forces due to impingement in a vacuum and at high altitudes. The static-load effects due to distance between the reaction nozzles and the impingement surface are of particular interest. Near-field studies, small separation distances – less than an exit diameter, are important for the design of such structures as plume deflectors and the problems associated with spacecraft thermal shielding, staging, docking, and ullage- and retro-rocket applications. For far-field effects hundreds of nozzle diameters away, the jet effects may be serious on such functional surfaces as large solar panels. The jet structures differ markedly for near-field and far-field studies. A complete mathematical model that incorporates such phenomena as the real-gas effects, the complex jet shock structures, and transition from isentropic to free molecular flow is presently beyond the state of the art. Because of the large number of variables involved, such as ambient pressure, chamber pressure, chamber temperature, mass flow, ratio of specific heats, exhaust nozzle configuration, and impingement surface geometry, simplified experimental studies are desirable in order to provide data for broadening one's insight into the problem and to obtain data trends for empirical definitions and designs.

The purpose of the present investigation was to determine the loads or forces induced by air and helium jets discharging normal to and impinging on a flat plate in a near vacuum, at sea-level conditions, and at an ambient pressure corresponding to an altitude of about 9 km. Small conical nozzles were employed. The effects of nozzle-exit Mach number and nozzle vertical displacement were determined by measuring the normal loads on the plate with a force balance. Previous tests for parallel jets impinging on the flat plate were made with the same nozzles and facilities; results of those tests were published in references 13 and 14.

SYMBOLS

The axis system, dimension nomenclature, and force relationships are illustrated in figure 1.

A_j	area of nozzle exit
d_j	diameter of nozzle exit
d_t	diameter of nozzle throat
F_N	static force on flat plate normal to surface
H	normal distance from plate to nozzle-exit plane

k, K	constants
M_j	jet-exit Mach number
\dot{m}	mass flow
p_a	ambient pressure in vacuum sphere
p_{ch}	total pressure or chamber pressure of nozzles
p_j	nozzle-exit static pressure
$\Delta p = p_{ch} - p_a$	
R	nozzle-exit Reynolds number, based on d_j
T_j	vacuum gross thrust of nozzle
V_j	jet-exit velocity
V_N	velocity component normal to flat plate
α_n	initial jet turning angle measured between nozzle center line and tangent to jet boundary at nozzle lip
γ	ratio of specific heats
θ_n	nozzle half-angle
ν_n	Prandtl-Meyer expansion angle from sonic velocity to nozzle-exit Mach number
ν_1	Prandtl-Meyer expansion angle from sonic velocity to jet-boundary Mach number

APPARATUS AND PROCEDURES

Nozzles

Six conical nozzles were available for the tests. They were employed to produce nominal jet-exit Mach numbers of 1, 3, 5, and 7 for air and 1, 3, 7, and 12 for helium. The exit Mach numbers and nozzle dimensions are summarized in figure 1(b). The

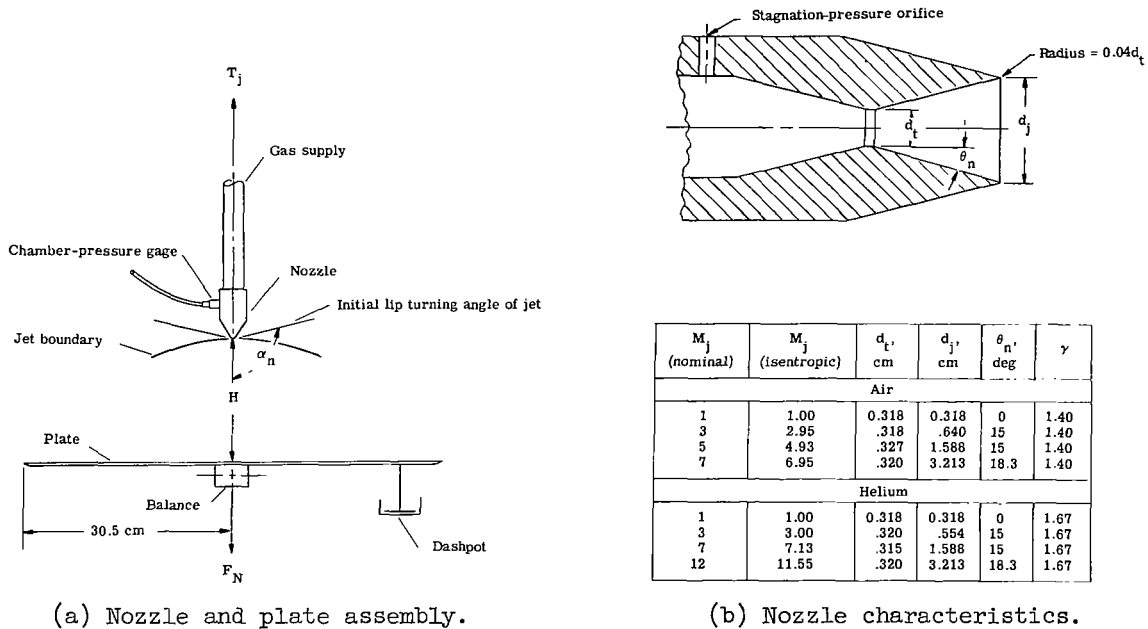
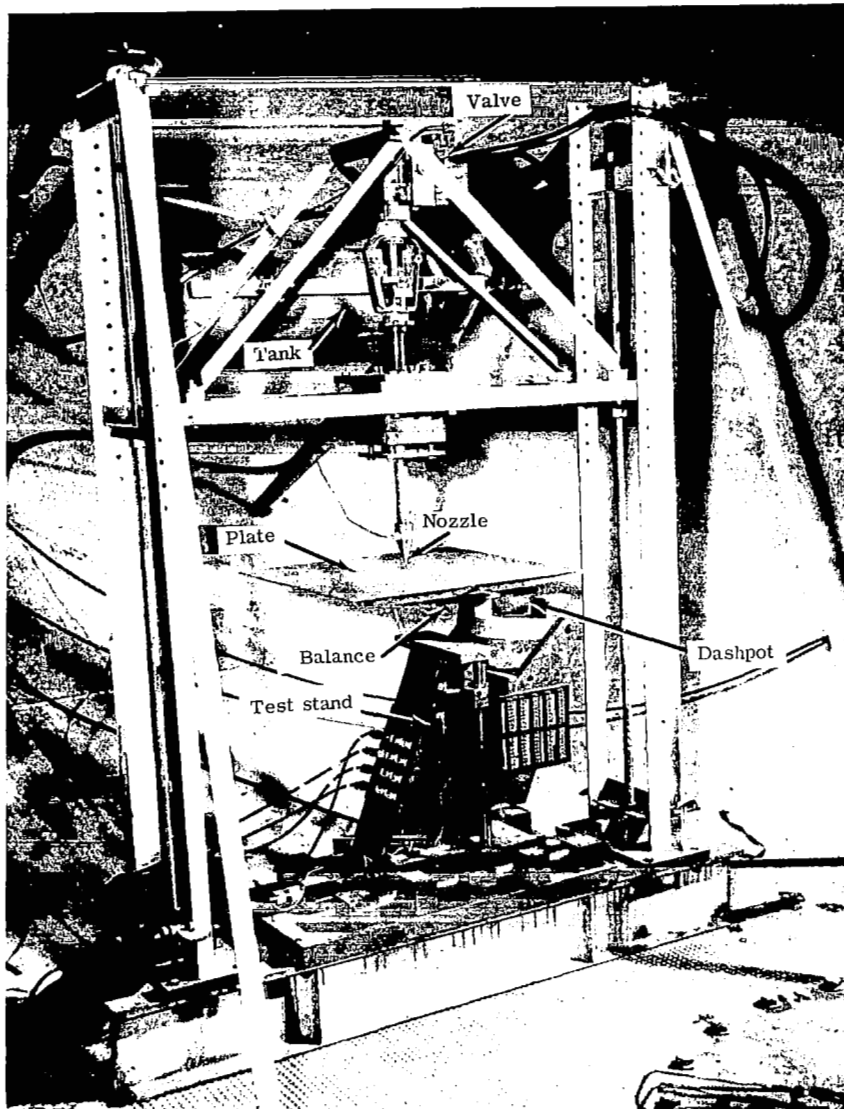


Figure 1.- Schematic representation of apparatus.

isentropic exit Mach numbers were based on the actual area ratios of the nozzles (by using data from refs. 15 and 16) and differed somewhat from the nominal or reference Mach numbers. The isentropic values of M_j were 1.00, 2.95, 4.93, and 6.95 for air; and, 1.00, 3.00, 7.13, and 11.55 for helium. Each nozzle tested was mounted on a rigid frame which was detached from the flat plate and balance setup. The nozzle vertical position was adjusted manually in steps of 15.24 cm. The plate vertical setting was varied within the nozzle steps through a remote-control system.

Tests and Setup

Tests were conducted in the 12.5-meter-diameter vacuum sphere at the Langley Research Center. The apparatus consisted of a flat smooth plate, a three-component balance, a dashpot, nozzles, a test stand, an oscillograph recorder, and plenum-chamber pressure gages. A schematic diagram and a photograph showing the general arrangement of the test apparatus are presented in figures 1(a) and 2, respectively. The variables investigated were nozzle-exit Mach number, ratio of specific heat (air or helium), vertical displacement of the nozzle from the flat plate, and pressure altitude.



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Figure 2.- Photograph of apparatus.

The plate surface had a smooth finish and was square with dimensions of 61 cm. Static loadings of the plate (greater than the anticipated maximum loading due to jet impingement) produced no measurable bending and thus the plate could be considered as rigid for the tests. A small rectangular aluminum block was attached to the geometric center of the bottom of the magnesium test-plate structure for mounting the balance. Attached to the test stand was a dashpot to dampen the amplitude of the oscillations induced on the test plate and balance by the jet impingement. The size of the test plate was made as large as possible, being limited by the specifications of the balance. The flat-plate area was about 47 000 times greater than the throat area of each nozzle.

The vertical displacement range for all the nozzles varied from approximately 0 to about 100 nozzle-exit diameters. The altitudes simulated were for quiescent air at approximately 95 km, 9 km, and sea level. The corresponding values of ambient pressure were 5×10^{-4} torr, 225 torr, and 760 torr (1 torr = 133.32 N/m²). The chamber pressure was held constant for each test. For most tests, the value of p_{ch} was within a range of 8000 torr to 12 000 torr. In a few cases, when vertical displacement was near 0, it was necessary to drop the chamber pressure to values near 150 torr in order not to overload the balance. The tests conducted and the chamber pressures employed are summarized in tables I and II. The ambient temperatures in the sphere varied between 280° K and 310° K.

Nozzle Gas Supply

The test gases, air and helium, were supplied to the nozzles through an accumulator and controlled by means of a pressure regulator and quick-opening valve located near the center of the vacuum sphere. This arrangement enabled an accurate control of the chamber pressure to be maintained for each test run. The nozzle chamber pressures were measured with two Statham pressure gages, one for the high and the other for very low pressures.

All the nozzles tested were highly underexpanded when operating in a near-vacuum ambient pressure (p_a of 5×10^{-4} torr). The jet lip turning angles as a function of the ratio of jet-exit static pressure (isentropic) to ambient pressure for all the nozzles are presented in figure 3. The turning angles obtained by using data from references 15 and 16 and the expression $\alpha_n = \nu_1 - \nu_n + \theta_n$ are shown in the figure to be close to the corresponding turning angles for a vacuum. At the lower altitudes, the Mach number 1 nozzles and, in some cases, the Mach number 3 air nozzle were underexpanded; all the others were overexpanded. It was not possible to operate these nozzles with under-expanded flow at the low pressure altitudes because the increased chamber pressure would have provided loads that exceeded the range of the balance. The nozzle center lines were aligned normal to the center of the flat plate and the balance in order to provide flow symmetry and a zero moment about the balance.

Measurements

A three-component balance measuring normal force, pitching moment, and axial force on the plate was employed; however, the last component was not used. The normal-force range of the balance was about 5 kg and was biased 2.5 kg by the mass of the flat-plate assembly.

The nozzle gross thrusts and exit pressures (neglecting correction for nozzle divergence angle) were computed as follows for each test by using the chamber pressures

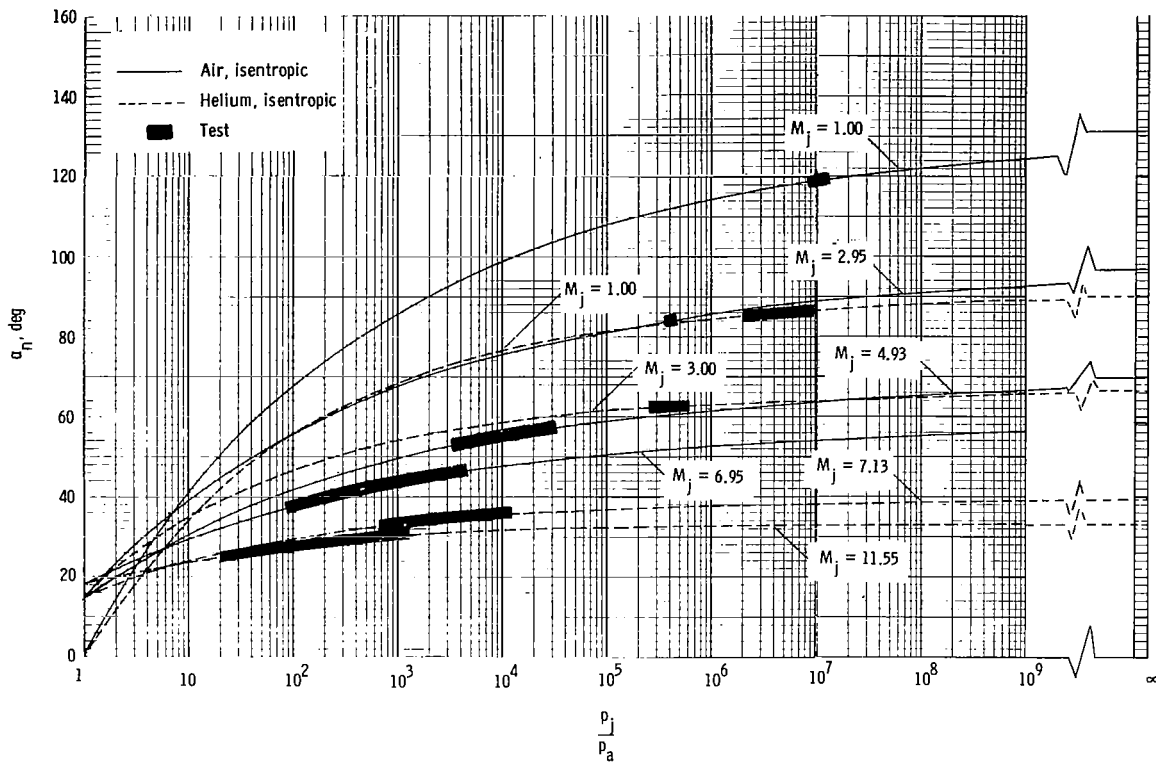


Figure 3.- Variation of initial turning angle with the ratio of jet-exit pressure to ambient pressure for the nozzles tested with underexpanded flow at a sphere pressure of 5×10^{-4} torr.

of tables I and II and assuming isentropic flow (using refs. 15 and 16) and a vacuum environment:

$$T_j = \dot{m}V_j + p_j A_j = p_{ch} A_j \left(\frac{p_j}{p_{ch}} \right) \left(1 + \gamma M_j^2 \right) \quad (1)$$

and

$$\frac{p_j}{p_{ch}} = \left(1 + \frac{\gamma - 1}{2} M_j^2 \right)^{-\frac{\gamma}{\gamma - 1}} \quad (2)$$

The ratio of normal force to gross thrust for a height or vertical displacement of 0 was computed by assuming that the total pressure acted over the area of the nozzle exit, as follows:

$$\frac{(F_N)_{H=0}}{T_j} = \frac{(p_{ch} - p_a) A_j}{T_j} = \frac{p_{ch} - p_a}{p_j} \left(1 + \gamma M_j^2 \right)^{-1} \quad (3)$$

Accuracies

The errors in the measurements, based on instrument accuracies, are summarized below for various conditions:

	Error
$F_N = 2.5 \text{ kg}$	0.03 kg
$p_{ch} = 13\,000 \text{ torr}$	150 torr
$p_{ch} = 2500 \text{ torr}$	30 torr
$p_a = 5 \times 10^{-4} \text{ torr}$	$5 \times 10^{-5} \text{ torr}$
$p_a = 225 \text{ torr}$	1 torr
$p_a = 760 \text{ torr}$	1 torr
$0.16 \text{ cm} \leq H \leq 15.00 \text{ cm}$	$2 \times 10^{-3} \text{ cm}$
$0 \leq H \leq 0.16 \text{ cm}$	$5 \times 10^{-4} \text{ cm}$

The vertical displacements H were measured as the perpendicular distance between the nozzle-exit plane and the surface of the unloaded plate. An additional displacement of the plate due to loading of the balance was determined experimentally to be less than 10^{-4} cm and, hence, negligible. The reference height of 0 was obtained by pressing the nozzle exit on the plate until the plate had a static load or bias of about 0.1 kg. The duration of each test was approximately 0.25 second. According to reference 17, the Mach number 5 and 7 air nozzles, which were operating under saturation temperatures and pressures, may have had a 10-percent reduction in exit Mach numbers due to condensation effects or two-phase flow.

RESULTS AND DISCUSSION

Basic Data

A sample oscillograph record is presented in figure 4 to show the traces of normal force, pitching moment, and nozzle chamber pressure for a typical run. The data points were read near the center of the data interval. This interval, as shown in figure 4, covered a time increment of about 0.1 second through which the data were nearly constant. Calculations of the change in ambient pressure in the sphere during a test showed that the test-pressure increase was infinitesimal.

The force data, the vertical displacement distances (heights), and the nozzle-exit static pressures were nondimensionalized by dividing by values of computed gross thrust, nozzle-exit diameter, and ambient pressure, respectively. It can be seen from the values of chamber pressures presented in tables I and II that some nozzle positions were investigated twice by using two distinct levels of pressure. The drop in p_{ch} , required

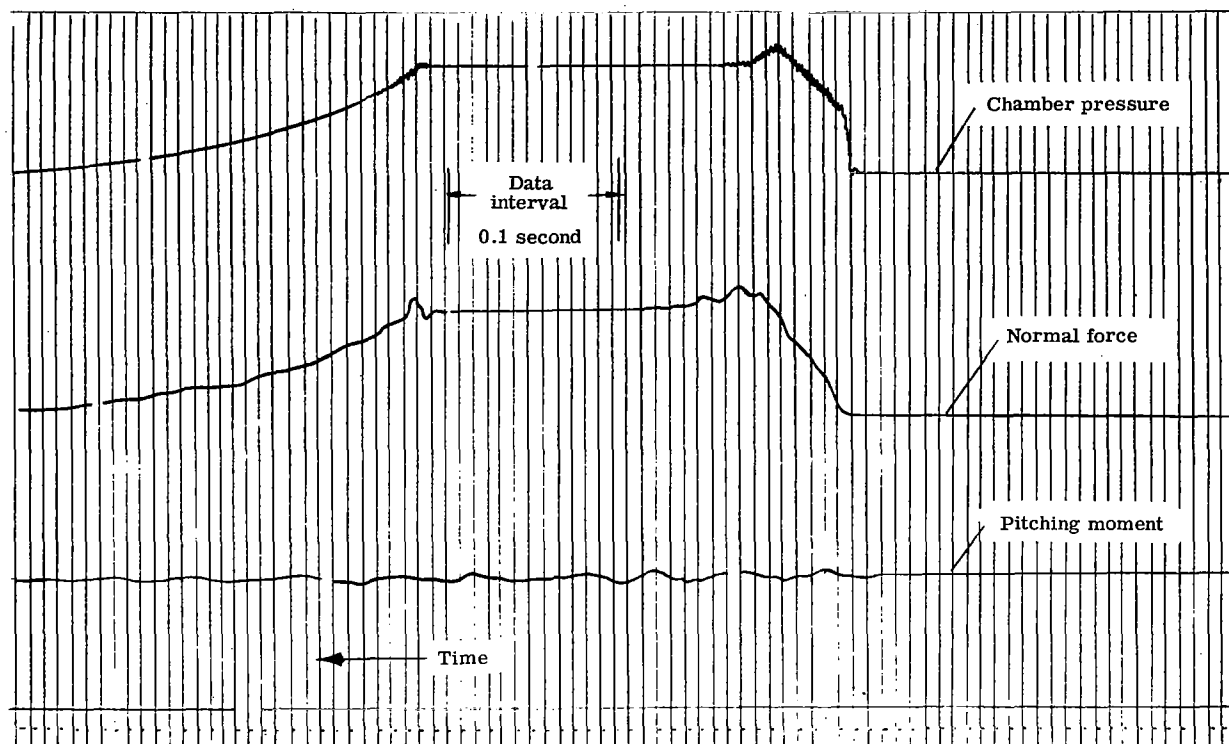
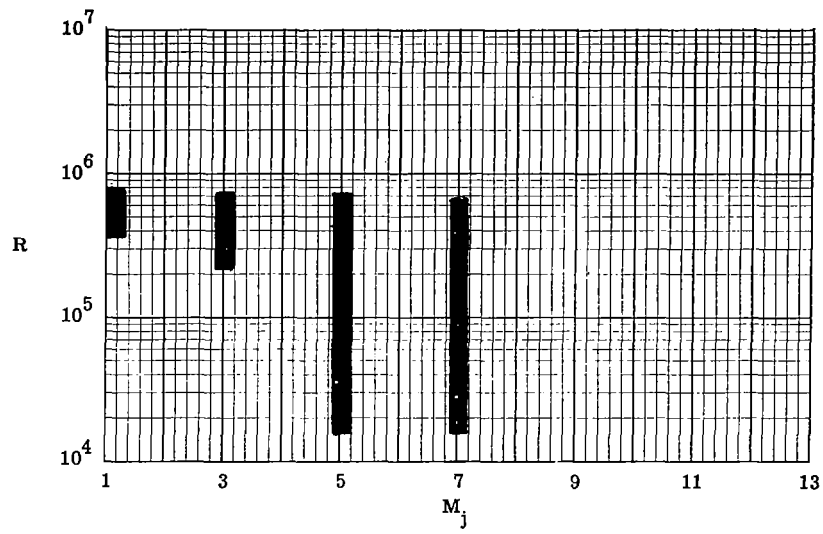


Figure 4.- Typical oscillograph record.

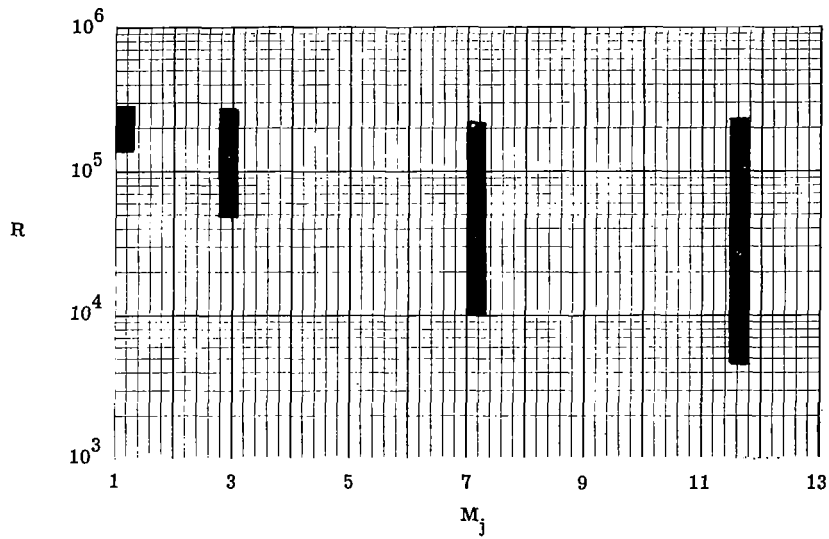
by the balance limit, provided data which indicated that the parameter F_N/T_j was not dependent on the mass flow rates or jet-exit Reynolds numbers for the ranges covered. The ranges of nozzle-exit Reynolds numbers, based on respective exit diameters, are presented in figure 5. For heights that were greater than $0.01d_j$, the test Reynolds numbers were about 500 000 for air and 200 000 for helium. The Reynolds numbers for heights between 0 and $0.01d_j$ were reduced slightly for the Mach number 1 and 3 nozzles and markedly for the high Mach number nozzles because of changes in chamber pressure.

Air Nozzle Tests

Near vacuum.- The variations of F_N/T_j with H/d_j for all the air nozzles tested are presented and compared in figure 6(a) for an ambient pressure of 5×10^{-4} torr. Since the ranges of the parameters measured were very large, it was necessary to compress the normal-force-parameter scale at the lowest values of H/d_j in order to present all the results in one figure. In fact, this change in scale enhances the value of the data since the chamber-pressure gage was changed in order to preserve the accuracy of measurements, especially for the lower values of F_N . The zero height or touchdown force ratios are plotted as flagged symbols near $H/d_j = 0.001$ on the log-based abscissa. The comparison indicates that the results fall into two regions, which may be referred to

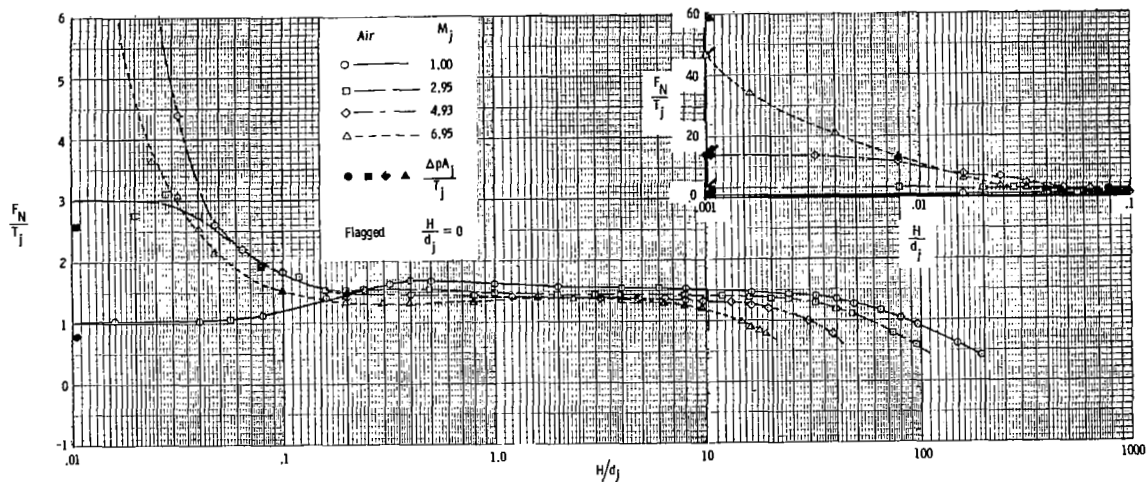


(a) Air.

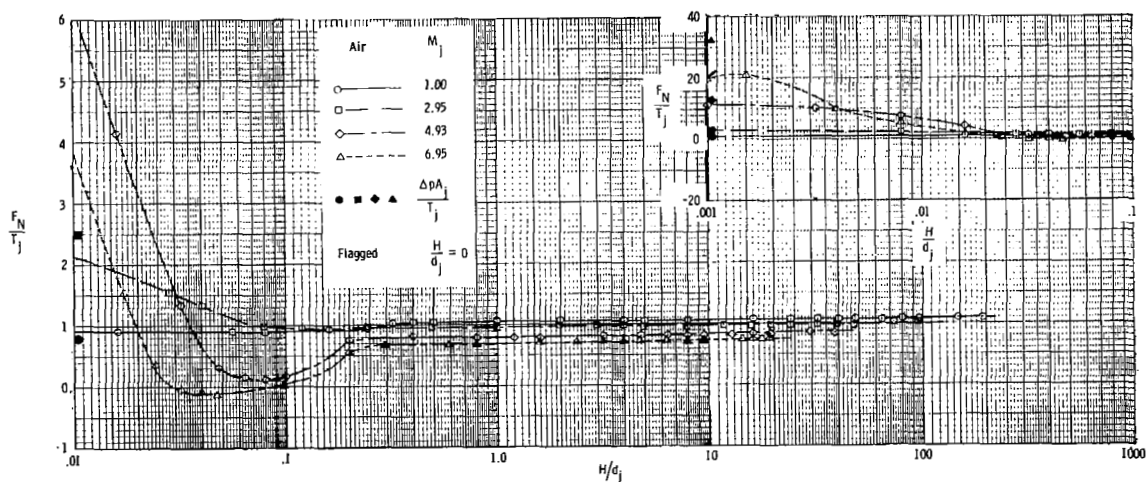


(b) Helium.

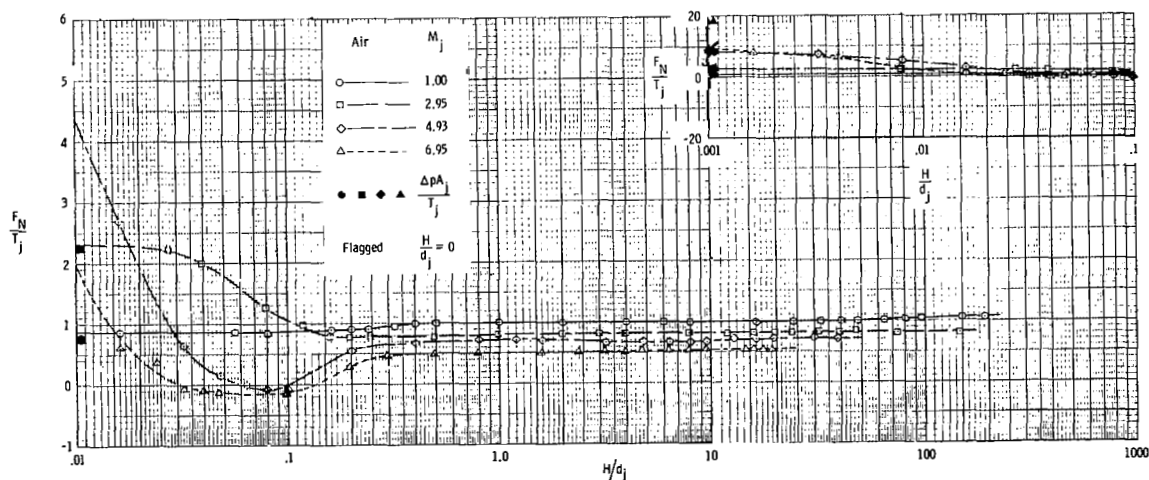
Figure 5.- Comparison of jet-exit Reynolds numbers for the nozzles. Reynolds numbers are based on exit diameters.



(a) Underexpanded flow at ambient pressure of 5×10^{-4} torr.



(b) Near-ideal expansion at ambient pressure of 225 torr.

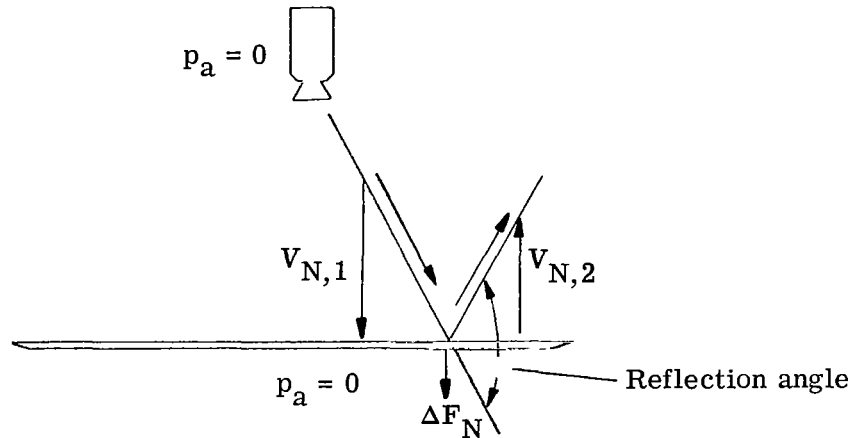


(c) Overexpanded flow at ambient pressure of 760 torr.

Figure 6.- Variation of the ratio of normal force to thrust with nondimensional height above the plate for air jets.

as far field and near field. It appears that the far-field region starts at a height of about $0.2d_j$ for all the nozzles since it is at this value that the ratio of force to thrust becomes nearly constant. The flat plate may be considered as infinite until the nozzle height is increased to the point where F_N/T_j begins to fall off. The decrease thereafter is due to spillage of the expanding flow over the edges of the plate.

For the far-field data, the Mach number 1 nozzle had a ratio of static force to thrust of 1.7 at a height of $0.4d_j$. This ratio dropped gradually to about 1.3 at $50d_j$. The force ratios decreased with increase in nozzle-exit Mach number. The Mach number 7 nozzle, which gave the smallest impingement force herein, had an average force ratio of 1.3 for heights between $0.2d_j$ and $10d_j$. The average value of F_N/T_j of all the nozzles shows that the far-field force on the plate due to normal jet impingement would be about 40 percent greater than the gross thrust of the nozzle used, even at considerable distances from the plate. The normal force in a vacuum is greater than the thrust owing to the change of the momentum of the jet. This result is similar to the examples in reference 18 for jet vanes or certain airfoils and may be explained by assuming that the flow exiting from the nozzle in a vacuum expands along straight streamlines. The streamlines are reflected off the plate, as illustrated in the following sketch for one streamline:



From the change of momentum normal to the plate,

$$\Delta F_N = \dot{m} \Delta V_N = \dot{m} (V_{N,1} - V_{N,2}) \quad (4)$$

where the relative velocity between the flat plate and nozzle is zero. Since $V_{N,2} = -kV_{N,1}$, equation (4) becomes

$$\Delta F_N = \dot{m} V_{N,1} (1 + k) \quad (5)$$

For the whole plate, the summation of ΔF_N can be approximated by assuming a one-dimensional change in momentum in the following manner:

$$F_N = \sum \Delta F_N = \dot{m}V_j(1 + K) \quad (6)$$

and the force ratio becomes

$$\frac{F_N}{T_j} = \frac{\dot{m}V_j(1 + K)}{\dot{m}V_j + p_j A_j} = \frac{1 + K}{1 + \frac{p_j A_j}{\dot{m}V_j}} \approx 1 + K \quad (7)$$

since $\frac{p_j A_j}{\dot{m}V_j} \ll 1$ for the nozzles tested. Also, it appears that the nozzle-exit Mach number effects were small for these near-vacuum tests. The average value of K for all tests was 0.4.

For the near-field results (values of $H/d_j < 0.2$), very large changes in normal force were obtained with variations in either distance or nozzle. These changes are similar to the changes in near-field, flat-plate pressures obtained in reference 1. The maximum values of F_N/T_j were obtained for the zero reference height and they were equal to 1.02, 3.01, 14.08, and 47.37 for the nozzles having exit Mach numbers of 1.00, 2.95, 4.93, and 6.95, respectively. Maximum theoretical values of F_N/T_j are shown in figure 6 as shaded symbols for comparison with the touchdown values. The theoretical maximum values represent the condition of nozzle blockage; that is, when the exit flow ceases and the exit pressure is equal to chamber pressure. Equation (3) and the results in figure 6(a) show that $(F_N)_{H=0}$ is very sensitive to nozzle-exit area. For vertical displacements between 0 and about $0.1d_j$, the results could not be readily predicted because the flow in the nozzle was complicated with oblique and normal shock waves, separated flow, and the existence of both supersonic and subsonic flows (ref. 5).

Low altitudes. - The variations of the ratio of normal force to thrust with nozzle displacement at ambient pressures of 225 torr (9-km altitude) and 760 torr (sea level) are presented in figures 6(b) and 6(c), respectively. The results obtained for these low-altitude tests are similar to each other. The Mach number 1 nozzle was underexpanded, the Mach number 3 nozzle was either slightly underexpanded or overexpanded, and the Mach number 5 and 7 nozzles were overexpanded. Only the Mach number 1 nozzle at 225 torr has far-field values of $F_N/T_j > 1.00$. The far-field force ratios also decreased

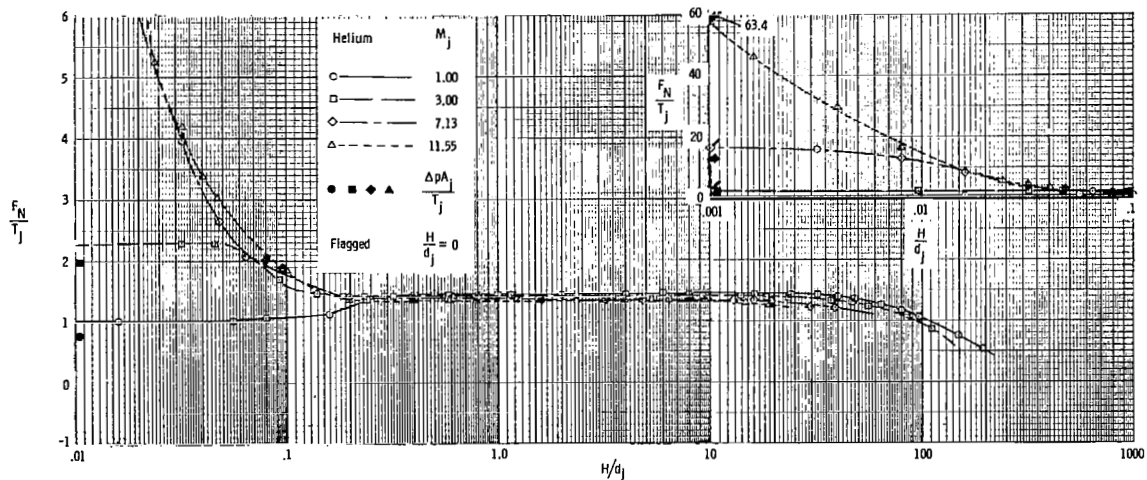
with increasing nozzle-exit Mach number; the lowest value was about 0.5 for the Mach number 7 nozzle at sea level. The far-field normal force levels for all the nozzles appeared constant up to the maximum vertical displacement. The near-field results were not systematic. The normal forces obtained from the Mach number 5 and 7 nozzles experienced a rapid and large drop between heights of about $0.2d_j$ to $0.02d_j$. At lower heights the forces approach their corresponding theoretical maxima (eq. (3)). The fact that the Mach number 5 and 7 nozzles produced negative normal force, for its lowest value, indicated that the jet interference produced lift on the plate in the atmosphere. A comparison of all the results in figure 6 shows that there are large and significant differences in the normal impingement loads between vacuum and low-altitude application. In general, raising the ambient pressure reduced the flat-plate loading.

Helium Nozzle Tests

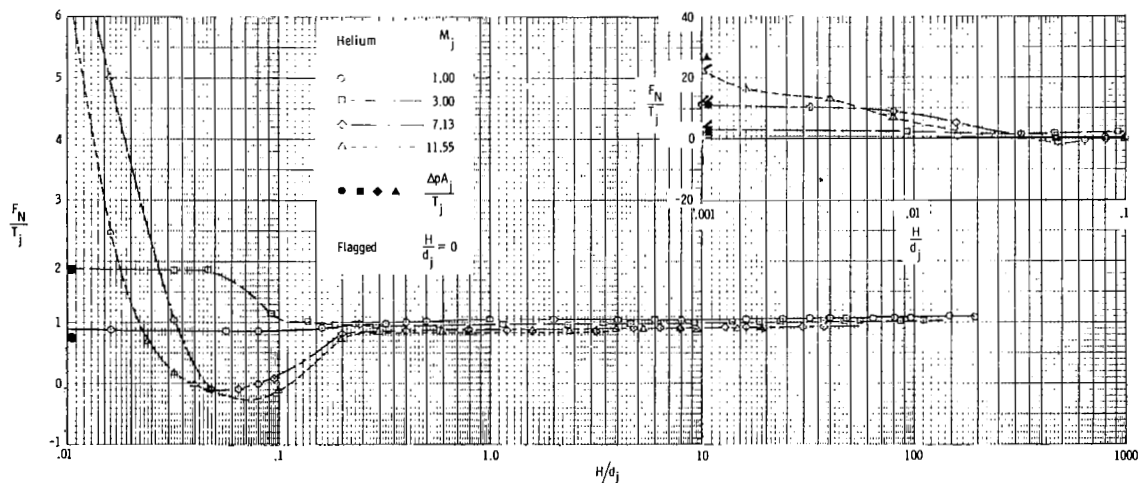
The impingement loads for all the helium nozzle tests are presented in figure 7. Although the Mach number ranges were different from those of the air nozzle tests, the magnitudes and trends closely approximate the results from air jets. Near-field effects (below $H/d_j \approx 0.2$) gave very large touchdown loads for the hypersonic nozzles. It is significant that in the far-field region the average value for F_N/T_j of all the nozzles under near-vacuum conditions also was about 1.4.

Correlation of Air and Helium

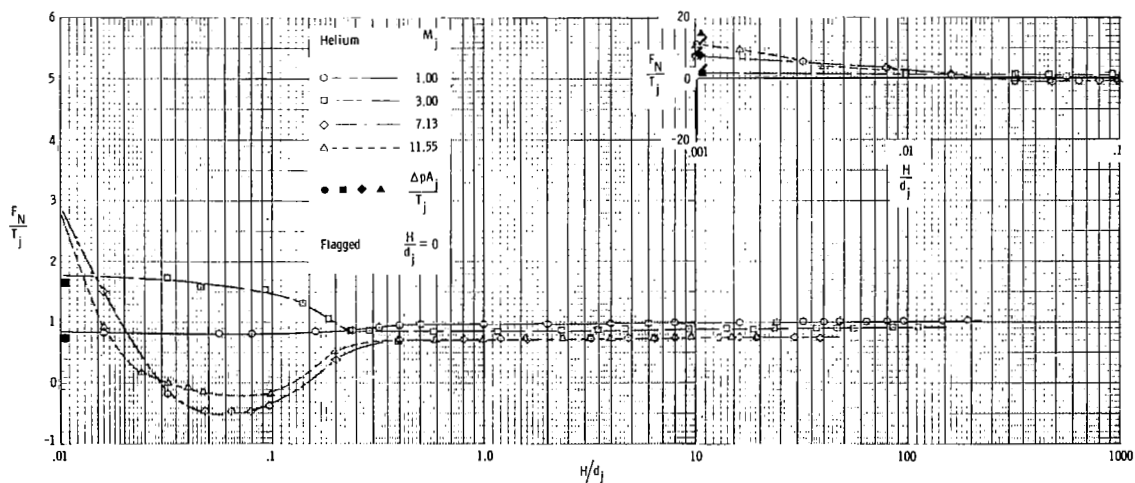
Jet-exit pressure ratio. - A correlation of the loads from both the overexpanded and underexpanded nozzles is presented for a far-field displacement of $1.0d_j$ in figure 8. The test-point symbols represent average values from the curves of figures 6 and 7. The loading on the flat plate was less than the gross thrust for all overexpanded nozzles. Loads greater than the gross thrust appeared to become significant for $p_j/p_a > 10$. The values of F_N/T_j for underexpanded flow continued to increase until the value 1.63 was reached at $p_j/p_a \approx 10^7$, the limit of the tests. Under the near-vacuum conditions, the reflection angles of the streamlines varied between 90° and 180° on the plate. If all the streamlines would have impinged normal to the plate, the reflection angles would have been 180° and F_N/T_j would have approached 2.0. This situation is analogous to perfectly elastic molecules rebounding perpendicularly to a wall in a vacuum. The amount of scatter of the data about the mean curve may have been due to such effects as different expansion angles, spillage off the plate, and experimental accuracy.



(a) Underexpanded flow at ambient pressure of 5×10^{-4} torr.



(b) Near-ideal expansion at ambient pressure of 225 torr.



(c) Overexpanded flow at ambient pressure of 760 torr.

Figure 7.- Variation of the ratio of normal force to thrust with nondimensional height above the plate for helium jets.

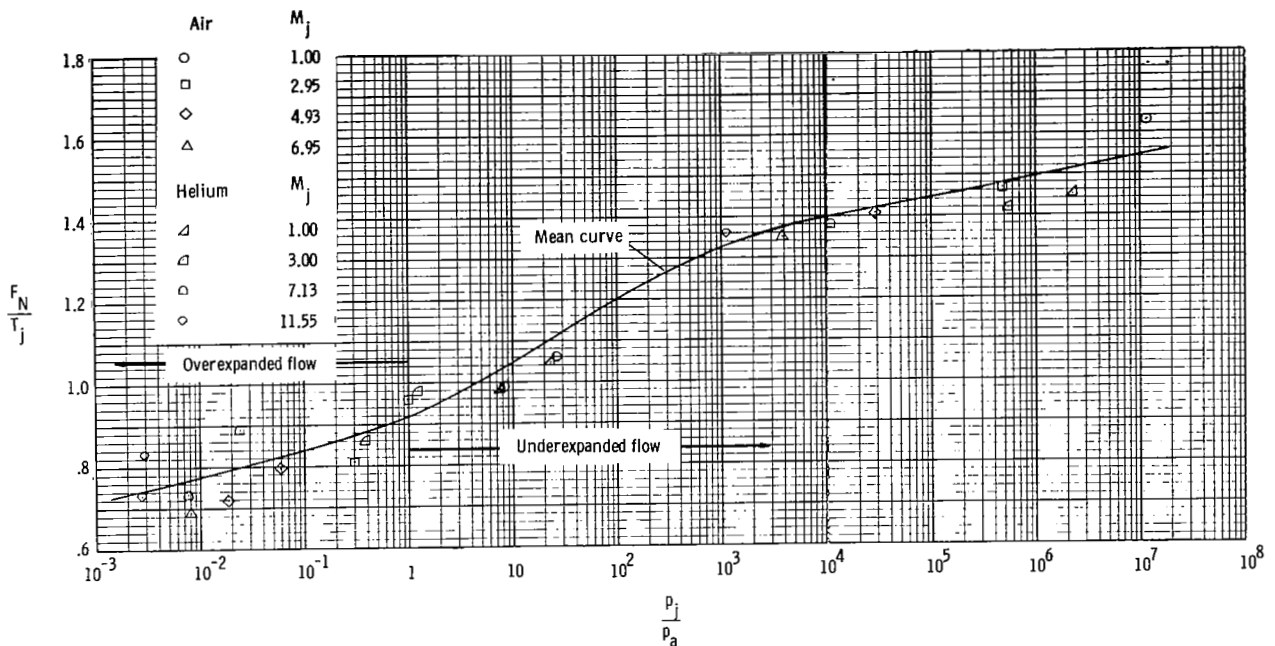


Figure 8.- Variation of the ratio of normal force to thrust with the ratio of jet pressure to ambient pressure for the air and helium jets at $H/d_j = 1.0$.

Maximum load.- For the purpose of design, the values of $(F_N)_{H=0}/T_j$ for all the tests have been plotted and compared with the maximum force parameter $(p_{ch} - p_a)A_j/T_j$. (See fig. 9.) The touchdown loading $(F_N)_{H=0}/T_j$ was greatest at the lowest ambient pressure. The ratios of normal force to thrust at 5×10^{-4} torr varied nearly linearly from about 1 for the Mach number 1 air or helium nozzle to about 60 for the Mach number 12 helium nozzle. As was indicated previously, the large variations in the maximum normal-force loading of the plate was dependent on the nozzle-exit area and nozzle chamber pressure.

The test results are compared with the line of perfect agreement in figure 9. In general, the Mach number 1, 3, and 5 nozzles for both gases produced slightly greater experimental values of maximum force than was obtained from the maximum force parameter. This incremental increase may be due to reflections of the leakage gas and/or experimental accuracy. The largest forces were obtained near touchdown at 5×10^{-4} torr and were approximately equal to the product of the chamber pressure and nozzle-exit area. The maximum forces from the corresponding higher Mach number nozzles dropped markedly as the ambient pressure was increased and thereby indicated a significant interaction between any leaking gas and the surrounding air.

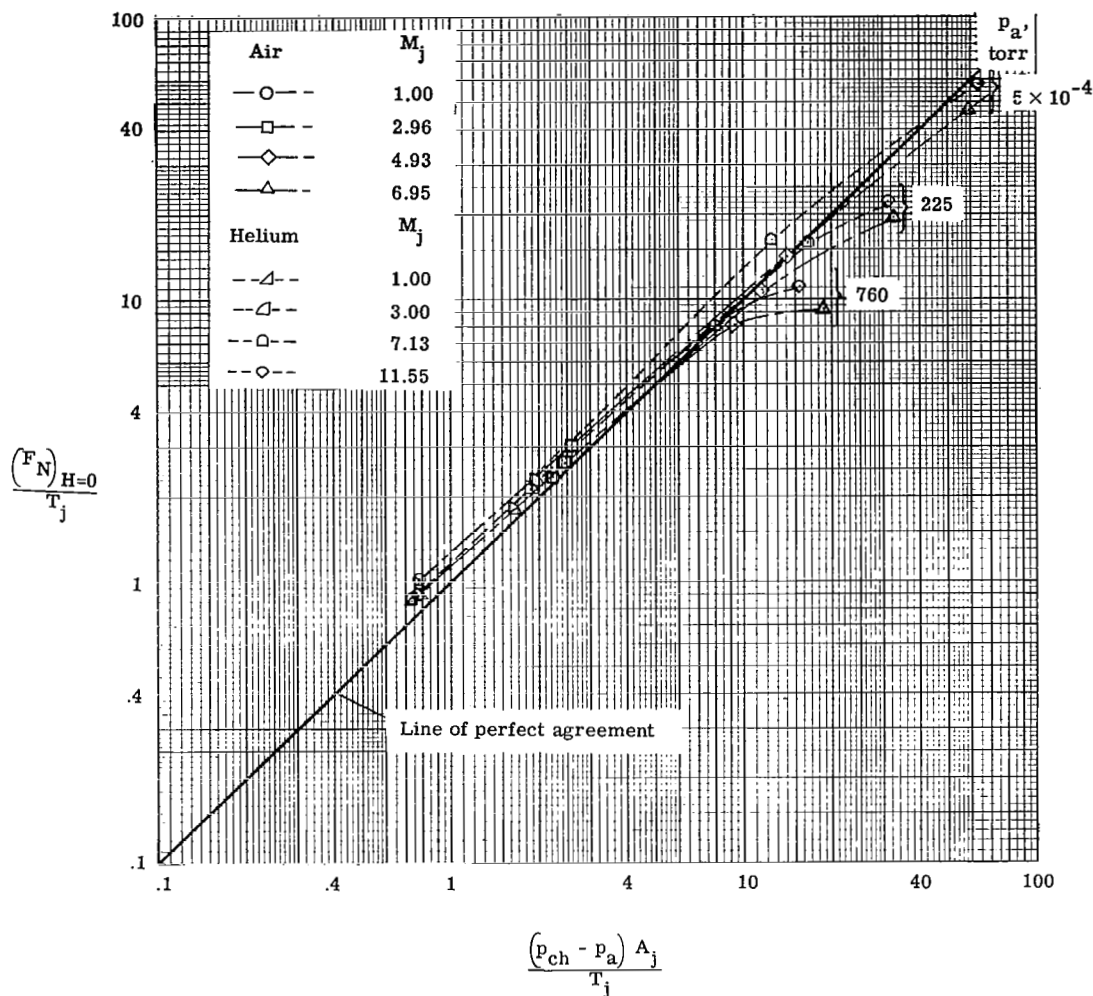


Figure 9.- Variation of the ratio of touchdown normal force to thrust with maximum force parameter for the air and helium jets.

CONCLUSIONS

An investigation was conducted in a vacuum sphere to determine the static loads due to air and helium jets impinging normal to a flat plate at ambient pressures of 5×10^{-4} torr, 225 torr, and 760 torr (1 torr = 133.32 N/m²). The nozzles had nominal jet-exit Mach numbers of 1, 3, 5, and 7 for air and 1, 3, 7, and 12 for helium. The vertical displacement of each nozzle was varied from touchdown to about 200 throat diameters above the plate. The following observations were made:

1. The variations of the ratio of normal force to gross thrust with nozzle height above the plate were similar for the air and helium jets tested under comparable conditions.

2. A demarcation existed between near-field and far-field impingement effects at a nozzle height equal to about 0.2 of the exit diameter.

3. For the far-field effects, the ratios of force to thrust were nearly constant up to the maximum displacements and the normal force had an average value of about 1.4 times the gross thrust (without spillage off the plate) under near-vacuum conditions. The changes in the ratio of normal force to thrust due to jet-exit Mach number and Reynolds number effects were small.

4. The ratios of normal force to gross thrust varied markedly with distance in the near-field region and were very sensitive to nozzle-exit area. The largest forces were obtained near touchdown at 5×10^{-4} torr and were approximately equal to the product of the chamber pressure and nozzle-exit area. This force varied from a value about equal to the thrust for the Mach number 1 air or helium nozzle to a large value equal to 60 times the thrust for the Mach number 12 helium nozzle.

5. Negative loads or lift were obtained at certain heights in the near-field region at ambient pressures of 225 torr and 760 torr from the hypersonic nozzles.

6. The normal static loading on the plate was less than the gross thrust for the overexpanded nozzles and greater when the nozzles were underexpanded and had a ratio of jet pressure to ambient pressure greater than 10.

7. In general, raising the ambient pressure reduced the flat-plate loading.

Langley Research Center,

National Aeronautics and Space Administration,

Hampton, Va., October 20, 1970.

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TABLE I.- AIR CHAMBER PRESSURE

H, cm	Air chamber pressure, torr, at ambient pressure, torr, of -											
	5 × 10 ⁻⁴	225	760	5 × 10 ⁻⁴	225	760	5 × 10 ⁻⁴	225	760	5 × 10 ⁻⁴	225	760
	M _j = 1.00			M _j = 2.95			M _j = 4.93			M _j = 6.95		
0	8 530	11 580	12 050	3 410	5170	5270	980	1400	2280	207	465	1030
.0051	8 640	11 530	12 050	3 410	5120	5270	980	1340	2220	207	465	1030
.0127	8 530	-----	-----	6 310	-----	-----	980	-----	-----	259	465 and 776	1030 and 2330
.0178	8 640	11 430	12 050	3 410	5020	5270	-----	1340	2280	-----	-----	-----
.0254	8 580	11 430	12 050	3 460	9150	5270	980	1340	2220	259 and 776	1760	2280
.0508	8 530	11 330	11 890	6 310	9150	9260	980	1340	-----	1600	1760	2280
.0635	8 690	11 380	11 890	8 690	8790	9260	2170	8170	7710	-----	-----	-----
.0762	8 530	11 330	12 000	6 310	9210	9260	980	1340	2220	1600	-----	2430
.1016	8 480	11 220	11 790	6 310	9150	9260	980	1340	2220	1600	1760	2380
.1270	8 480	11 170	11 790	6 310	9210	9260	980	1340	2220	1600	1760	2380
.1588	8 480	10 960	12 100	6 260	9210	9260	1030	1340	2220	1500	1760	2330
.3175	11 070	11 330	11 790	8 690	8640	9310	1030 and 7600	1340 and 7710	2220 and 7710	1500 and 7760	1760 and 8020	2330 and 8270
.6350	11 070	11 380	11 790	8 790	8690	9310	7710	7710	7810	7710	8020	8270
1.2700	11 070	11 380	11 840	8 790	8790	9310	7710	8020	7710	7710	8020	8270
1.9050	11 070	11 380	11 790	8 790	8890	9360	7710	7960	7810	7710	8020	8270
2.5400	11 070	11 380	11 840	8 790	9410	9360	7710	7650	7810	7910	7710	7760
5.0800	10 810	10 760	11 530	7 760	7860	8070	7710	8120	8530	7910	7860	7810
7.6200	10 910	10 760	11 380	7 760	7860	8120	7650	8120	8430	7910	7860	7650
10.1600	10 760	10 760	11 380	7 760	7500	7910	7550	8120	8480	7910	7860	7650
12.7000	10 910	10 760	11 380	7 760	7600	7910	7550	8220	8530	7910	7860	7600
15.2400	10 910	10 760	11 270	7 760	7600	8020	7550	8070	8280	7910	7860	7760
20.3200	10 550	10 760	10 650	10 600	7600	8020	7650	8120	8690	7910	7860	7710
25.4000	10 550	10 760	10 860	10 600	7600	8070	7650	8270	8740	7910	7860	7760
30.4800	10 550	10 710	10 810	10 600	7650	8020	7650	8070	8690	7910	7710	7810
46.9900	10 810	10 710	10 960	7 710	7710	7600	7760	8220	8840	8070	7860	7810
50.8000	-----	-----	-----	-----	-----	-----	-----	-----	-----	7910	7550	7860
55.8800	-----	-----	-----	-----	-----	-----	-----	-----	-----	7910	7550	7960
60.9600	10 760	10 860	10 960	7 710	7710	7600	7760	8220	8740	7860	7650	7810

TABLE II.- HELIUM CHAMBER PRESSURE

H, cm	Helium chamber pressure, torr, at ambient pressure, torr, of -											
	5 × 10 ⁻⁴	225	760	5 × 10 ⁻⁴	225	760	5 × 10 ⁻⁴	225	760	5 × 10 ⁻⁴	225	760
	M _j = 1.00			M _j = 3.00			M _j = 7.13			M _j = 11.55		
0	8 690	11 720	11 480	4550	5020	5120	517	672	1500	155	414	1030
.0051	8 690	11 220	11 480	4550	5020	5120	517	672 and 1550	1500	155	414	1030
.0127	-----	-----	-----	-----	-----	-----	517 and 1450	1500	1500	259	414 and 879	1030
.0178	8 530	11 720	11 480	4450	4960	5120	1450	1500	1500	879	879 and 1810	1030 and 2380
.0254	8 640	11 720	11 430	4450 and 8530	4910 and 8640	5020 and 9150	1450	1500	1500	931 and 1550	1810	2330
.0508	8 480	10 960	11 330	8530	8580	9150	1450	1500	1500	1550	1810	2330
.0762	8 480	10 860	11 270	8480	8580	9050	1450	1500	1500	1600	1810	2330
.1016	8 480	10 810	11 020	8530	8580	9100	1450	1500	1500	1550	1810	2330
.1270	8 480	10 860	11 120	8480	8580	9050	1450	1500	1500	1600	1810	2280
.1588	8 480	10 600	11 790	8480	8790	9100	1450 and 1550	1500 and 7910	1500 and 8120	1550 and 8530	1810 and 8790	2280 and 9410
.3175	10 550	10 710	11 640	8530	8690	9100	1450 and 7500	1500 and 8020	1500 and 8120	8640	8790	9410
.6350	10 450	10 710	11 640	8530	8690	9150	7500	8020	8120	8640	8790	9310
1.2700	10 390	10 550	11 530	8480	8690	9150	7500	7910	8120	8640	8790	9410
1.9050	10 600	10 710	11 580	8530	8640	9100	7550	7910	8120	8640	8790	9310
2.5400	10 910	10 860	11 580	8530	8640	9100	7550	7910	8170	8640	8430	9150
5.0800	10 910	10 960	11 580	8530	8690	9050	7550	7910	8170	8690	8480	9100
7.6200	10 810	10 860	11 580	8530	8690	9100	7550	7860	7960	8690	8790	9150
10.1600	10 760	10 960	11 530	8530	8690	9100	7500	7860	8120	8690	9050	9260
12.7000	10 760	10 960	11 580	8530	8690	9100	7500	7860	8120	8790	8950	9260
15.2400	10 600	10 960	11 580	-----	-----	-----	-----	-----	-----	-----	-----	-----
20.3200	10 810	10 960	11 430	8530	8790	9150	7500	7860	8020	8890	8950	9310
25.4000	11 020	10 710	11 430	8690	8790	9150	7500	7860	8120	8890	8950	9260
30.4800	10 760	10 960	11 170	8530	8790	9150	7550	7860	8120	8690	8950	9260
46.9900	10 760	11 330	11 580	8480	8380	9260	7500	7500	8020	8690	8690	8890
60.9600	11 720	11 220	11 580	8530	8580	9310	7550	7400	8020	8640	8790	8890

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